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ORBITAL RENDEZVOUS CONSIDERATIONS

FOR A MARS MISSION

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This paper presents an analysis of a Mars-orbit-rendezvous concept. Attention is given to the use of rendezvous at Mars in light of the constraints placed by the requirement for tangential approach to and departure from Mars orbit for achievement of propulsive efficiency. A scheme is devised wherein orbital altitude and inclination are chosen so that the nodal and apsidal motion associated with Martian oblateness results in a tangential orbital launch at the time of departure. This scheme is discussed in the light of several rendezvous plans proposed for use in Earth operations.

INTRODUCTION

In recent years the NASA Langley Research Center has devoted considerable effort to investigation of the lunar-orbit-rendezvous mission. A substantial amount of this work has been concerned with rendezvous and the associated orbital and trajectory analysis. At the present time studies are being conducted on the more general aspects of interplanetary missions. This paper summarizes a brief investigation of the application of the concept used in the lunar-orbit-rendezvous plan to the manned Mars landing mission. This Mars-orbit-rendezvous mission has been considered in various forms by investigators and has already gained some degree of acceptance because of the substantial weight saving relative to the direct mission wherein all components of the space vehicle are landed on Mars. In the present study attention is given to the rendezvous

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problem at Mars in light of rendezvous plans that have been advanced for use in Earth orbit. The purposes of the present paper are to illustrate the basic considerations associated with Mars rendezvous operations, and to determine the applicability of various rendezvous plans. There are problems that must be considered in the use of the Mars-orbit-rendezvous mission. These problems are:

1. The direction of departure from the planet does not in general correspond to the direction of approach. This fact means that an efficient tangential orbital launch is not necessarily possible from the orbit originally established.

2. The planetary oblateness of Mars causes a nodal regression and apsides precession of orbits established at Mars which results in changes in orientation of the orbit in proportion to the stay time at Mars. This effect must be taken into account.

One solution to the use of rendezvous at Mars is to establish the rendezvous orbit at an altitude and inclination which satisfies the requirements of access to the desired latitude and at the same time produces nodal and apsidal motions which place the orbit in position for an efficient launch to Earth return. This solution is the approach taken in this investigation. The result will be illustrated first for circular rendezvous orbits. In this case the nodal motion is the only orbital perturbation of concern. Afterward the more general case of elliptic orbits will be treated. In this case both nodal and apsidal motions must be considered.

DEFINITIONS

The Mars-Orbit-Rendezvous Mission

The Mars-orbit-rendezvous mission considered is very similar to the lunar-orbit-rendezvous mission in that a command module and return propulsion are placed in orbit about the target planet, and descent is made in a smaller landing vehicle. Return to the command module is made at the end of the mission for orbital launch to Earth return. The mission sequence of the Mars-orbit-rendezvous mission is shown in Fig. 1.

Rendezvous Concepts

Three orbital rendezvous procedures are considered in this investigation. These plans are the orbital adjacency concept, the rendezvous compatible orbit concept, and the parking orbit concept. These plans are illustrated in Figs. 2, 3, and 4. Each of these plans may be used to explore various latitudes by the Mars-orbit-rendezvous concept with certain limitations. Mars has a day of about 24-1/2 hours and a substantial atmosphere, so there is a degree of similarity in Earth and Mars rendezvous situations.

The adjacency concept involves establishment of a rendezvous orbit at an inclination slightly higher than the latitude of the desired landing site. See Refs. 1, 2, 3, and 4. This operation results in a substantial period in each Martian day when the landing site is close to the orbital plane and an efficient launch to rendezvous may be made. Fig. 2 shows a situation in which the landing site is located at about 30° to 45° latitude and the orbit for rendezvous operations has an inclination 5° greater than the latitude of the landing site. The resulting launch window during which no plane change greater than 5° is required spans about 6 hours. During this 6-hour period all near Mars orbits (that is, those not exceeding a maximum altitude of 2,000 nautical miles) will have passed within 5° of the landing site at least twice, with the closer orbits passing within 5° as many as four times. A similar situation involving Earth orbits having maximum altitudes of 800 nautical miles or less would have only one additional passage for a total of five passes. The total penalty, descent and ascent, of the 5° plane change is about 5 percent of the total characteristic velocity required. A parking orbit or chasing technique may be used to eliminate the necessity for dependence on strict launch timing in rendezvous (Ref. 5). Access to various longitudes is generally available by choice of the time of descent.

The rendezvous compatible orbit concept as studied by Petersen and Swanson (Ref. 6) involves the choice of orbits which have periods that are about an even fraction of the planetary day so that the orbiting unit passes in proper relationship to the launch site for rendezvous at the time that planetary rotation carries the launch site through the orbital plane. See Fig. 3. In the most complete sense these orbits may be chosen in altitude and inclination so that a proper rendezvous relationship is achieved on each intersection of the launch site with the rendezvous orbit. For the purpose of this investigation the less complete definition of once-a-day compatibility will be used so that other use may be made of orbital inclination. Use of the rendezvous compatible orbit concept enables landings to be made at all latitudes less than the maximum inclination of the orbit established.

The parking orbit concept is illustrated in Fig. 4. In this plan launch is made into a parking orbit when planetary rotation carries the launch site through the rendezvous orbital plane, and transfer to the rendezvous orbit is made at a later time when the phasing between the orbiting command module and launch vehicle is proper. The parking orbit concept has been considered in various quarters and may be an integral part of other rendezvous plans such as the adjacency concept.

ANALYSIS

1975 Mission

In order to simplify the discussion of this paper a particular Mars stopover trip has been chosen. This trip is shown in Fig. 5 and involves a March 1975 Earth departure, a 50-day stay at Mars beginning in November of 1975, and a September 1976 return date to Earth. The total trip time is 550 days, and the closest approach to the Sun is about 0.7 astronomical units. See Ref. 7.

Fig. 6 shows the direction of approach to and departure from Mars for the mission selected for illustration. These directions are referred to the Mars-Sun line. It will be noted that the approach is made from in front of the oncoming planet and at about 60° to the Mars-Sun line. Departure is made to the rear of the receding planet and at about 50° to the Mars-Sun line. It is characteristic of a number of interesting missions that approach is from in front and departure toward the rear, with the angle to the Mars-Sun line being in the range of 40° to 70° for both approach and departure.

Orbits for Tangential Approach and Departure

Illustration of departure problem. Suppose that tangential entry is made into a polar orbit. See Fig. 7. Once established, the polar orbital plane is fixed, since planetary oblateness does not cause a regression of a polar orbit. Departure in a direction other than parallel to the tangential entry requires a plane change. In the case shown, which is for the 1975 trip considered, the direction of departure when orbital launch is made back to Earth would require a substantial plane change to be made.

Approach to Mars orbit. Fig. 8 indicates the general situation at approach to Mars; a similar figure with the directions of the velocity vectors reversed would indicate the departure condition. The approach velocity to orbit V_A is very nearly parallel to the velocity of central impact, and for efficient interplanetary transfer about parallel to the plane of the ecliptic. For tangential entry to a Mars orbit the approach velocity may take any position about the velocity of central impact. All the orbital planes that may be approached tangentially intersect along the velocity of central impact. Any particular orbital plane is thus defined by this velocity of central impact and the particular approach velocity (Ref. 8). Placing the approach velocity in the appropriate position to establish a given orbital plane may be accomplished as part of the midcourse corrections while the vehicle is still far from Mars.

Orbital entry and departure with a single impulse may be made with minimum characteristic velocity when the approach or departure is tangent to the desired orbit at its periapsis. The benefit of the periapsis maneuver is shown in Fig. 9. A formulation of this problem is given in Ref. 9.

Nodal and Apsidal Conditions

The relationship between orbital inclination and longitude of line of nodes which results from requiring that the orbital plane at Mars be parallel to the approach or departure velocity may be derived by analogy from the simplified expression given in Ref. 8. This relationship is:

$$\Omega = k + \delta \pm \Omega \tag{1}$$

where:

k takes the values 0, π, or 2π to establish the proper quadrant

$$\delta = \tan^{-1}(\tan \alpha \cos \beta)$$

$$\Omega_i = \sin^{-1}\left(\tan i_{min}/\tan i\right)$$

$$i_{min} = \sin^{-1}\left(\left|\sin \alpha \sin \beta\right|\right)$$

The positive sign on Ω_i is used for northerly approaches and departures and the negative sign for southerly approaches and departures.

The expression for the argument of periapsis of the Mars orbit that is required for entrance into or departure from orbit at periapsis may be derived from considerations of orbital mechanics and the geometry of the problem. This relationship is:

$$\psi = k \pm \theta \pm \psi_i \tag{2}$$

where:

k takes the values 0, π, or 2π to establish the proper quadrant

$+\theta$ is used on approach and $-\theta$ on departure

$+\psi_i$ is used for southerly approach and departure

$-\psi_i$ is used on northerly approach and departure

These formulations assume the approach to Mars to be in the plane of the ecliptic. Similar expressions may be obtained for the more general case. The solutions to expressions (1) and (2) for the mission of this study are shown in Figs. 10 and 11. Fig. 10 shows orbital inclination as a function of longitude of line of nodes. Fig. 11 shows orbital inclination as a function of argument of periapsis. The orbits available on approach are shown by the solid-line curves; those available on departure are shown by the dashed-line curves. Similar plots may be made for any chosen mission. Orbits having inclinations less than 90^o have a component of orbital velocity in the direction of Mars' axial rotation and are indicated as being "corotating." Those having inclinations greater than 90^o have a component of velocity opposite to the direction of Mars' axial rotation and are indicated as being "contrarotating." The advantage of utilizing the corotating orbital planes for propulsive efficiency in landing and launch is readily apparent. The letters N and S indicate the hemisphere in which orbital approach or departure is made (north or south).

It may be noted in Figs. 10 and 11 that there is a band of orbital inclinations near the equator that is not available on arrival and a smaller band that is not available on departure. The band that is prohibited on arrival extends about 25° on either side of the equator and corresponds to the inclination of Mars' equator with respect to the ecliptic. These bands vary with the particular approach and departure time and direction considered and are thus a function of the mission chosen.

Figs. 10 and 11 show that there is a difference in the nodal and periapsis positions of arrival and departure orbits. However, there is a motion of these orbits either regressive or progressive as indicated by the wavy arrows on these figures. If an orbit were established on arrival such that these motions would, in the stay time specified, rotate the orbit appropriately, then an orbital launch from periapsis without the necessity of a plane change could be achieved.

Orbit Motion Rates

Figs. 12 and 13 show the nodal and apsidal regression and progression rates for several elliptic orbits at Mars (Ref. 10). Circular orbits having a radius equal to the semimajor axis of these elliptic orbits will have somewhat different rates of motion. The values shown in these figures are based on a 24-hour day. The regression rate for a 30° inclined 200-nautical-mile circular orbit at Mars is about 9° a day. This case gives 40 days for a complete nodal regression of 360°. There is a zero precession rate of the line of apsides for orbits inclined at 63.4°. The apsidal motion at this inclination is oscillatory.

RESULTS

Circular Mars Orbits

For circular Mars orbits a simple situation presents itself. In this case the argument of periapsis is undefined and the only consideration of significance is nodal position. The altitude of orbit for operations at Mars may be chosen for a given inclination of orbit so that the orbit initially assumed at Mars will regress because of planetary oblateness to the nodal position required for tangential departure. Choosing regression rates that will in 50 days place the orbit in the proper position for tangential departure at the first, second, or third intercept of the departure nodal position curve results in the orbits shown in Fig. 14. The first, second, and third intercepts correspond to 1, 2, and 3 launch opportunities during the 50-day stay for the mission considered here. Only results for corotating orbits are shown. Those orbits not falling on one of these curves are not admissible orbits for a 50-day stay followed by tangential departure for Earth. It should be noted that the admissible orbits become narrower in range of inclination and of lower altitude as the number of launch opportunities in 50 days is increased from 1 to 2 and 3. The symbols in combinations of N and S indicate the hemisphere for approach to orbit and departure at the end of 50 days. N-S for instance indicates entrance into orbit in the northern hemisphere and exit from orbit in the southern hemisphere. A delay in orbital launch involves a plane change which is small if the delay is not excessive. A delay of 9 days in orbital launch for a

1,000-nautical-mile orbit corresponds to a nodal difference of 30°. For a 30° inclined orbit, this nodal difference requires a plane change of about 15°.

The adjacency rendezvous concept may be used in this circular orbit situation. Establishment of the rendezvous orbit at the proper inclination will enable access to a range of latitudes at Mars. However, some latitudes are excluded for tangential approach and departure particularly in the vicinity of the equator. A plane change at orbit entry removes these restrictions.

Use of the rendezvous compatible orbit concept enables landings to be made at any latitude less than the maximum inclination of the rendezvous orbit with assurance of an attractive rendezvous situation. Fig. 15 shows the discrete orbits from the curves of Fig. 14 that have the feature of once-a-day rendezvous compatibility. These orbits also satisfy the nodal requirement for tangential launch to Earth return, of course. A wide range of orbits is available, indicating a substantial degree of flexibility in the use of this concept.

Elliptic Mars Orbits

Some mission analyses have indicated the desirability of establishing elliptic orbits at Mars for overall mission propulsive efficiency. Approach to and departure from an elliptic orbit should be made in the orbital plane and tangent to the periapsis for best efficiency. This requirement necessitates satisfying two conditions at both entrance and departure from orbit. One of these is the nodal condition, and the other is the periapsis condition. The maximum altitude of the elliptic rendezvous orbit at Mars may be chosen for a given inclination of orbit to satisfy either one of these two conditions by making use of the data of Figs. 10 to 13. The points where the resulting curves intersect satisfy both conditions.

The results of such an analysis for the mission used to illustrate this report are given in Fig. 16. Only the curves where intersections between the nodal and periapsis conditions were obtained are shown. The curves in the lower left-hand corner of the figure are associated with more rapid nodal and apsidal motions. In these cases the nodal and periapsis conditions for larger angular displacements are satisfied. The symbols involving N and S indicate entrance and departure from the northern or southern hemisphere. Only intersections that agree in this regard are physically realizable, of course. These results are for corotating orbits.

Four intersections are shown in Fig. 16. Two are at very low altitudes where satisfying the apsidal condition is of little importance from a propulsive standpoint. Two others are at an altitude of about 2,000 nautical miles and an inclination of about 70°. No other intersections exist at higher altitudes for the mission considered here. Access to various latitudes from one of these orbits would in general require use of the parking orbit rendezvous concept mentioned previously in that the choice of inclination required by the adjacency technique is not available here since both inclination and altitude are specified in satisfying both the nodal and periapsis conditions. In the case considered here, one of the rendezvous compatible orbits is close to these intersections. This orbit is indicated for the S-S approach and departure by the triangular symbol. Use of this rendezvous compatible orbit rather than the intersection where the nodal and periapsis condition is satisfied perfectly only results in a misalinement of the line of apsides from a periapsis launch by about 15°. Fig. 9 shows that this misalinement causes only a small propulsive penalty. This point illustrates that satisfying the conditions developed in this paper in an exact way is not necessary in that the propulsive penalty is not great for reasonable perturbations. Only when large differences from periapsis launch or large orbital plane changes are involved does the penalty become substantial.

CONCLUDING REMARKS

The Mars-orbit-rendezvous mission places substantial constraints on the orbits that may be used at Mars for rendezvous operations. However, it is possible to select orbits which may be used with rendezvous techniques studied for Earth operations to make an efficient operational plan for exploration of the various latitudes at Mars. Specifically the Mars orbits may be chosen so that efficient tangential approach to and departure from Mars orbit may be made. This result is accomplished by making use of the nodal and apsidal motions associated with the oblateness of Mars.

NOTATIONS

h_a	apoapsis altitude, nautical miles
h_p	periapsis altitude, nautical miles
N	occurrence of tangency condition in northern hemisphere
S	occurrence of tangency condition in southern hemisphere
RCO	rendezvous compatible orbit
r_m	radius of surface of Mars, ft
$r_{H,p}$	periapsis radius of a hyperbolic orbit, ft
$V_{C,m}$	circular satellite velocity at surface of Mars, fps
$V_{H,\infty}$	hyperbolic excess velocity, fps
V_{CI}, $V_{\text{central impact}}$	velocity for radial approach or departure, fps

V_A tangential approach velocity, equal and parallel to the V_{CI} of approach, fps

V_D tangential departure velocity, equal and parallel to the V_{CI} of departure, fps

l_o latitude of landing and take-off site, degs

i orbital inclination, degs

i_{min} $\sin i_{min} = \left|\sin \alpha \sin \beta\right|$, minimum orbital inclination, degs

α direction of approach or departure with respect to the ecliptic node, degs

β inclination of Mars' equator with respect to the ecliptic, degs

δ $\tan \delta = \tan \alpha \cos \beta$, angular distance from ecliptic node to meridian of V_{CI}, degs

θ $\cos \theta = -1 \Big/ \left[1 + \left(\frac{r_{H,p}}{r_m}\right)\left(\frac{V_{H,\infty}}{V_{C,m}}\right)^2\right]$, angular distance from periapsis to V_{CI} in plane of hyperbolic orbit, degs

k angle used to establish proper quadrant for Ω and ψ, takes on values of 0, π, and 2π

$\Omega = k + \delta \pm \Omega_i$ location of ascending node of possible orbit about Mars, degs

positive sign of Ω_i for northerly approach and departure

negative sign of Ω_i for southerly approach and departure

Ω_i $\sin \Omega_i = \tan i_{min} / \tan i$

$\psi = k \pm \theta \pm \psi_i$ location of periapsis of hyperbolic approach or departure with respect to the ascending node of the orbit, degs

positive sign for θ on approach

negative sign for θ on departure

positive sign for ψ_i on southerly approach and departure

negative sign for ψ_i on northerly approach and departure

ψ_i $\sin \psi_i = \left| \sin i_{min} / \sin i \right|$

$\dot{\Omega}$ nodal regression rate, degs/day

$\dot{\psi}$ apsides precession rate, degs/day

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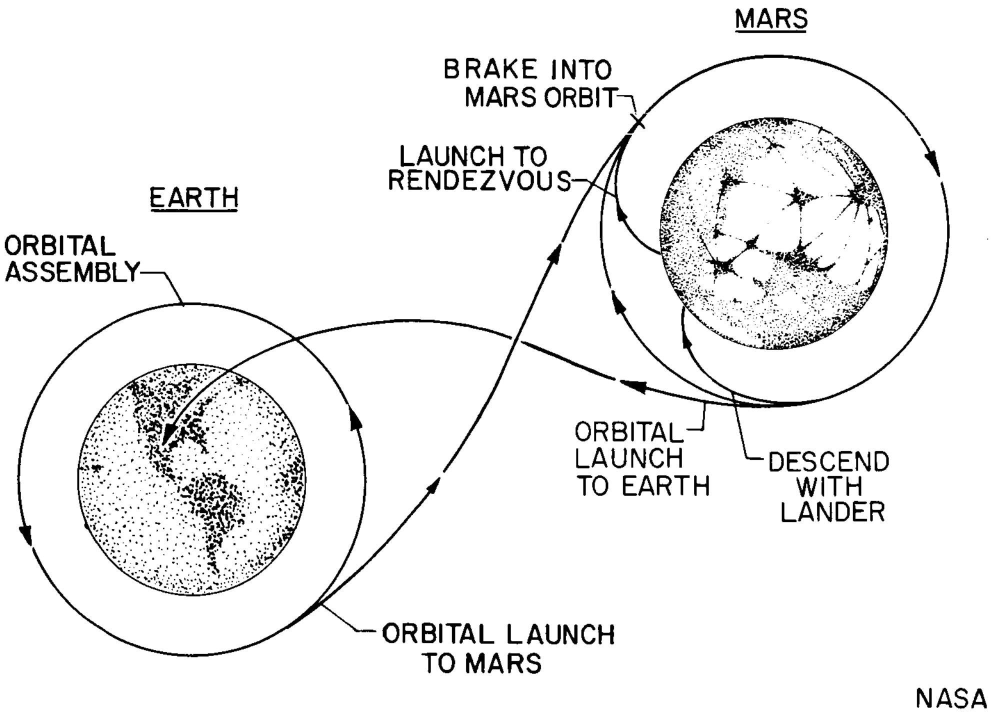

Figure 1.- Mars-orbit-rendezvous mission sequence.

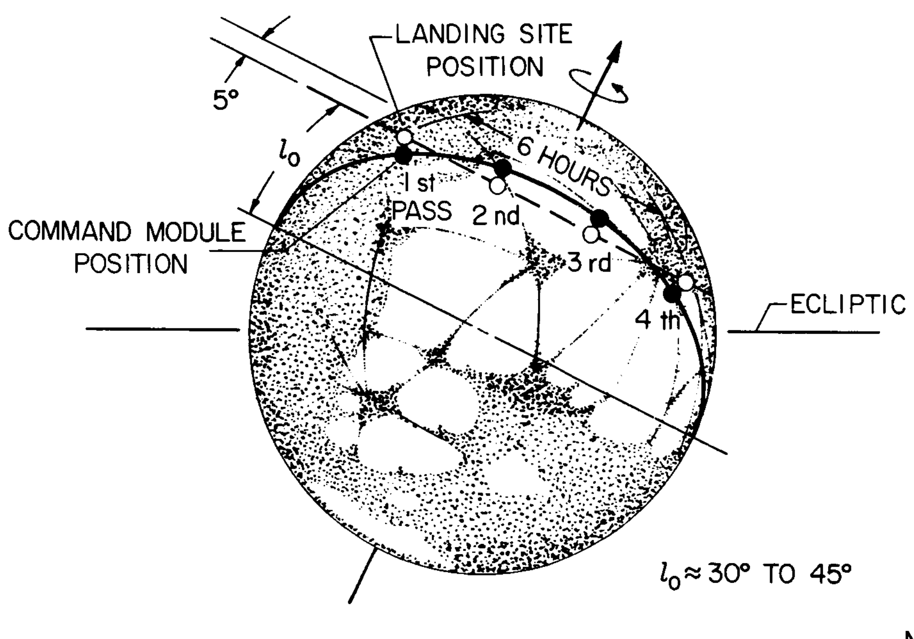

Figure 2.- Orbital adjacency for rendezvous. Close orbits at Mars.

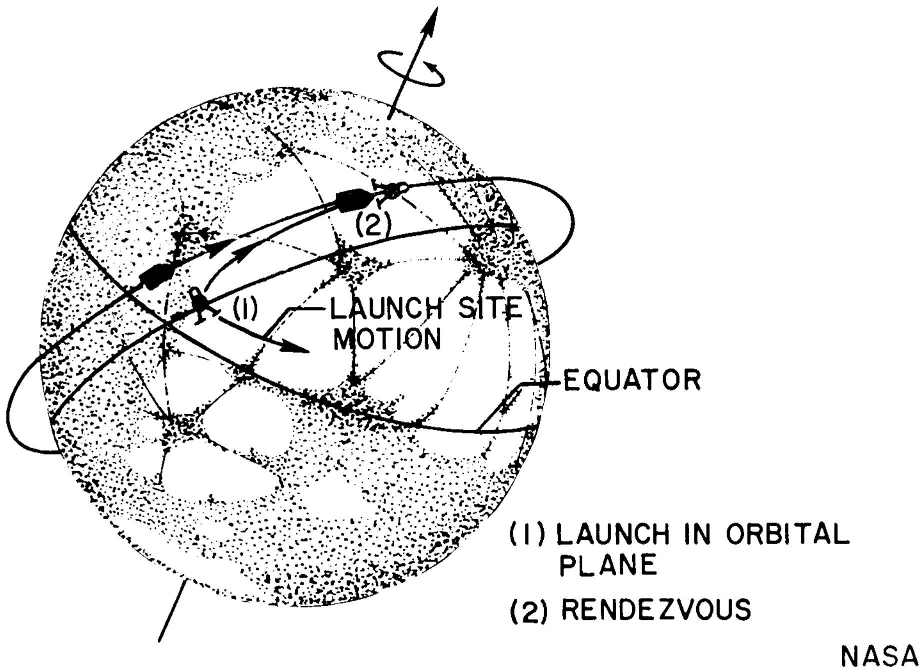

Figure 3.- Compatable orbits for rendezvous.

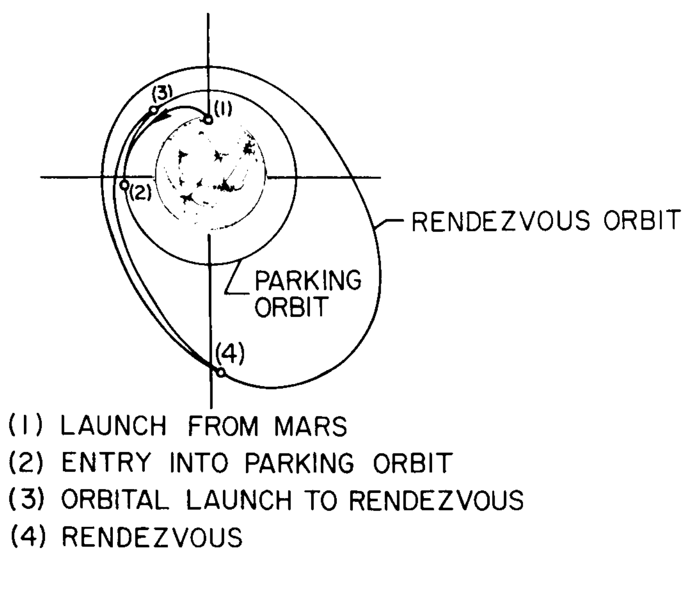

Figure 4.- Parking orbits for rendezvous.

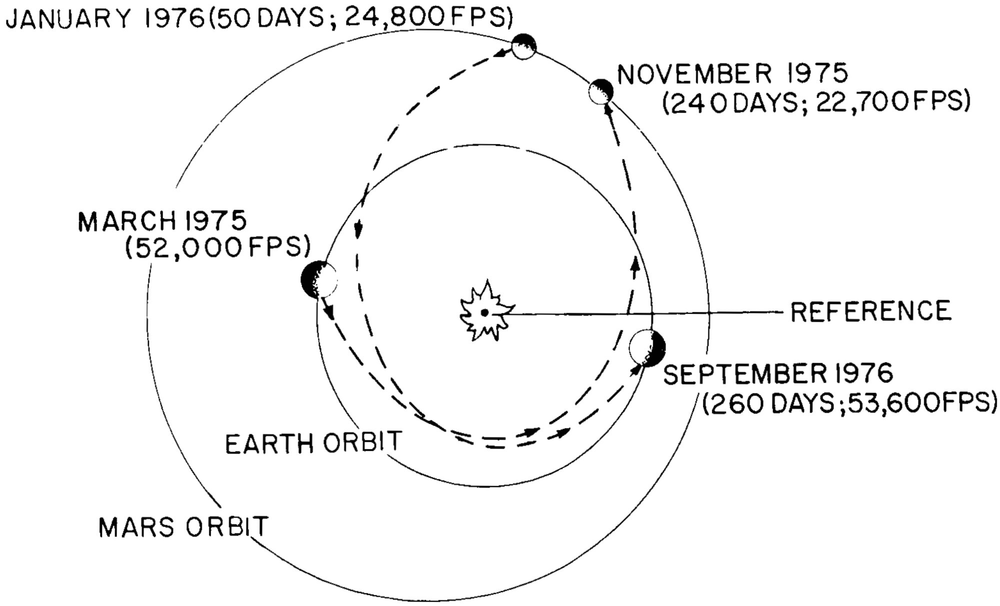

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Figure 5.- 1975 mission.

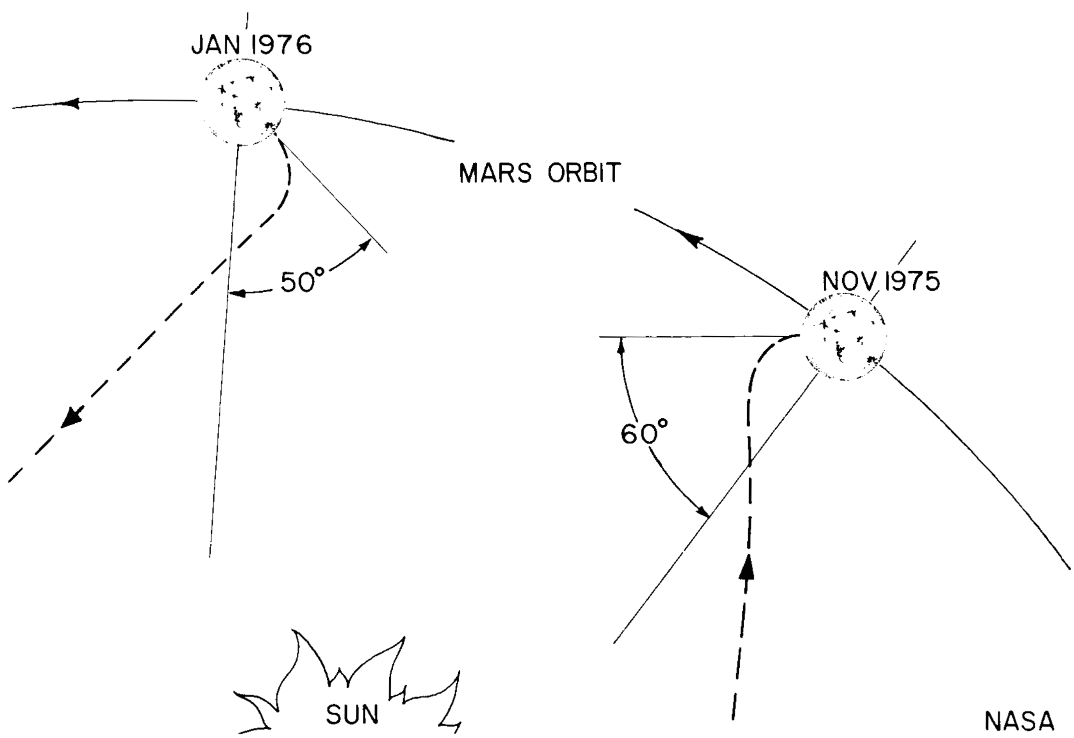

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Figure 6.- Direction of approach and departure.

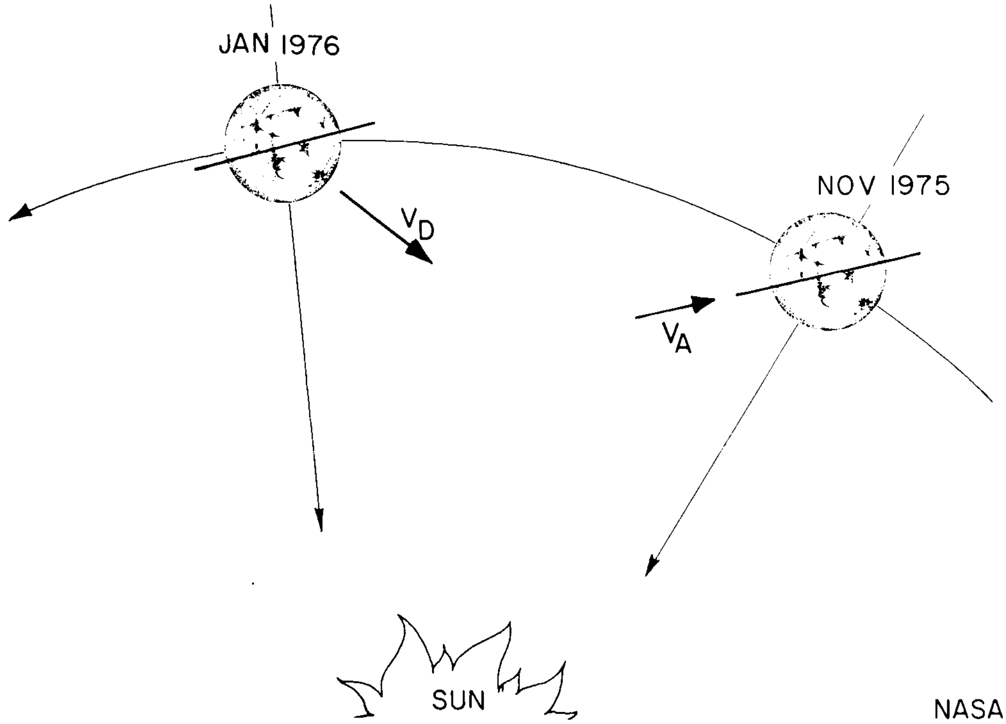

Figure 7.- Departure from polar orbit.

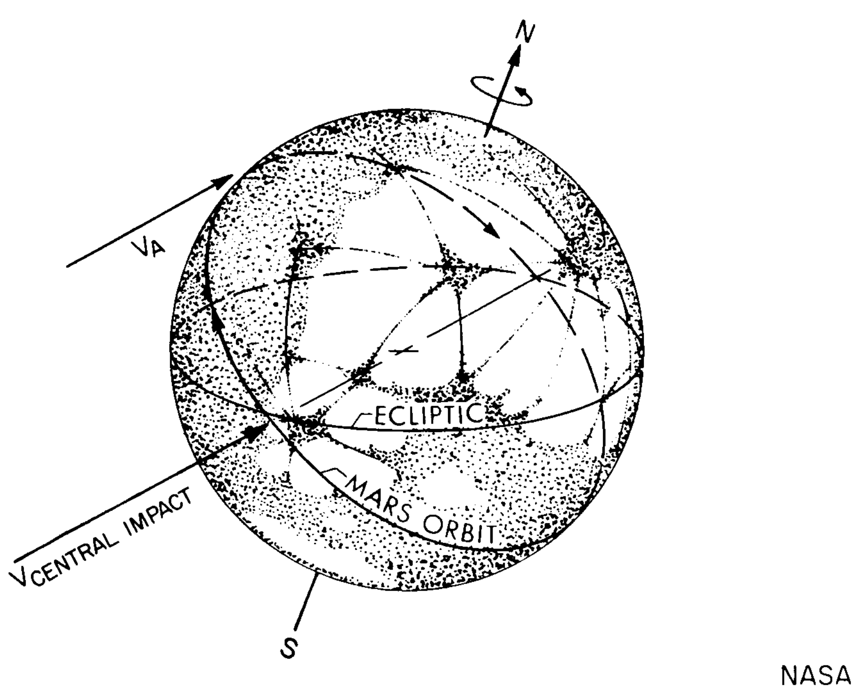

Figure 8.- Approach to Mars orbit.

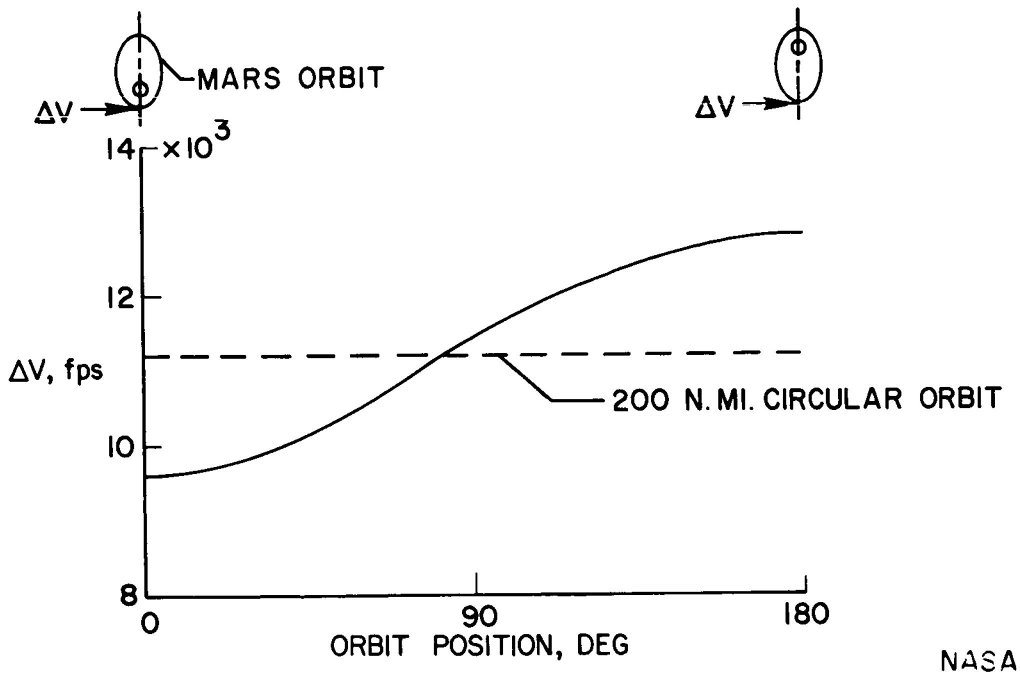

Figure 9.- Propulsive effort for entrance into elliptic orbits. h_p = 200 N. Mi; h_a = 2000 N. Mi.

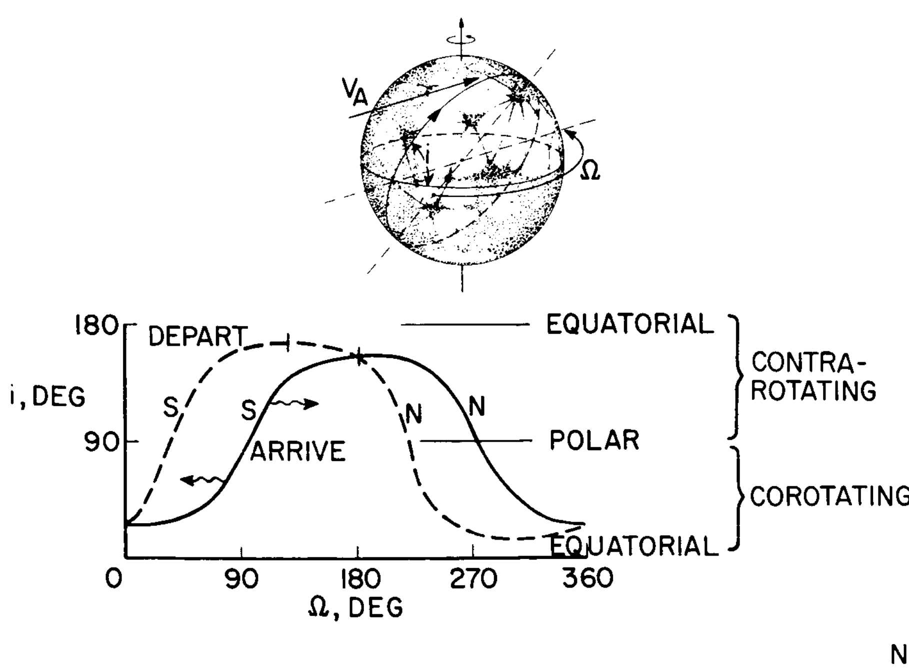

Figure 10.- Nodal positions of orbits for tangential approach and departure, 1975 mission.

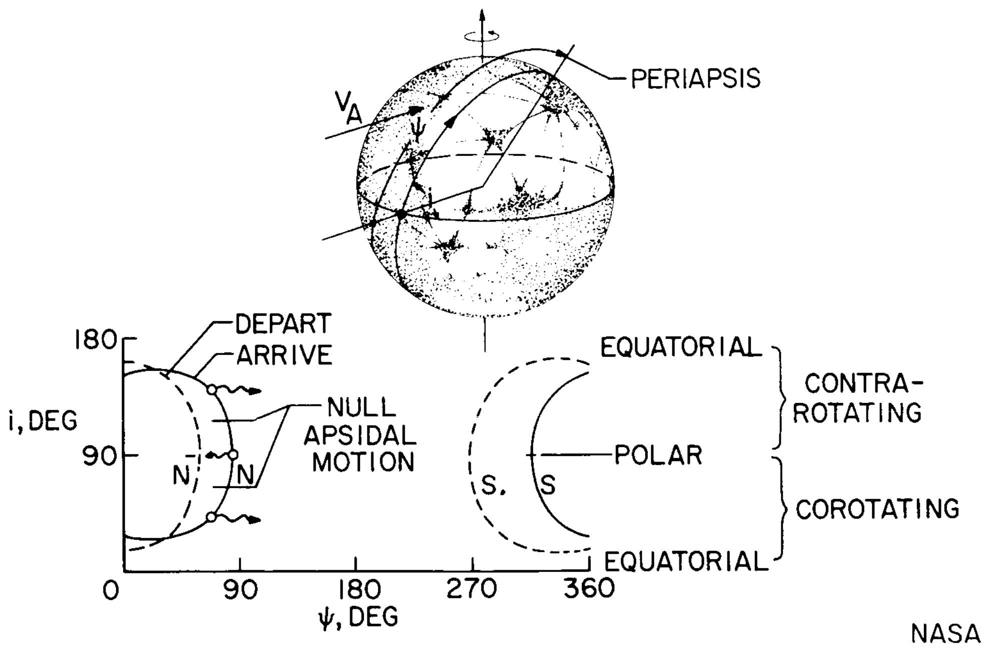

Figure 11.- Apsidal positions of orbits for tangential approach and departure, 1975 mission.

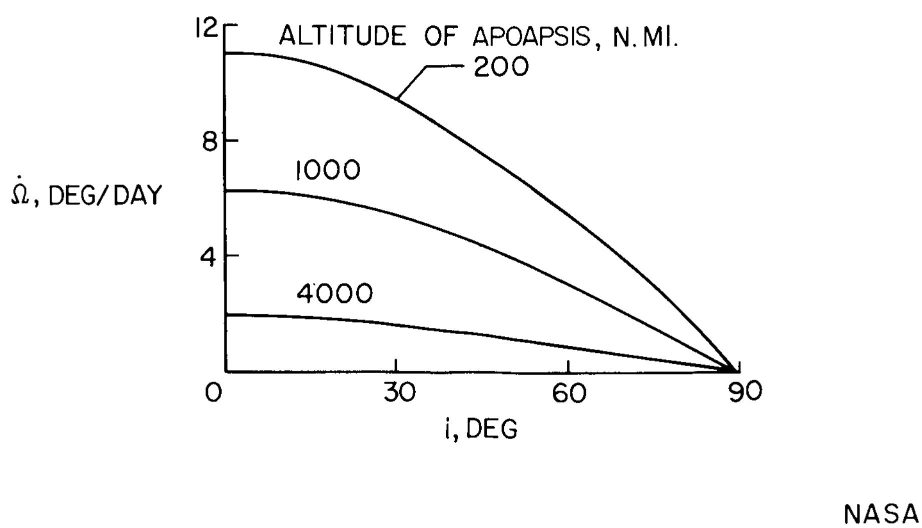

Figure 12.- Nodal regression of elliptic Martian orbits. Periapsis at 200 N. Mi. altitude.

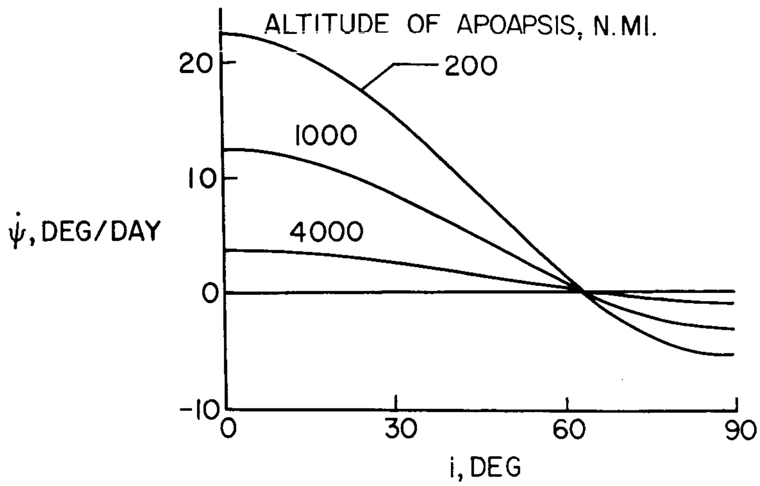

Figure 13.- Apsidal motion of elliptic Martian orbits. Periapsis at 200 N. Mi. altitude.

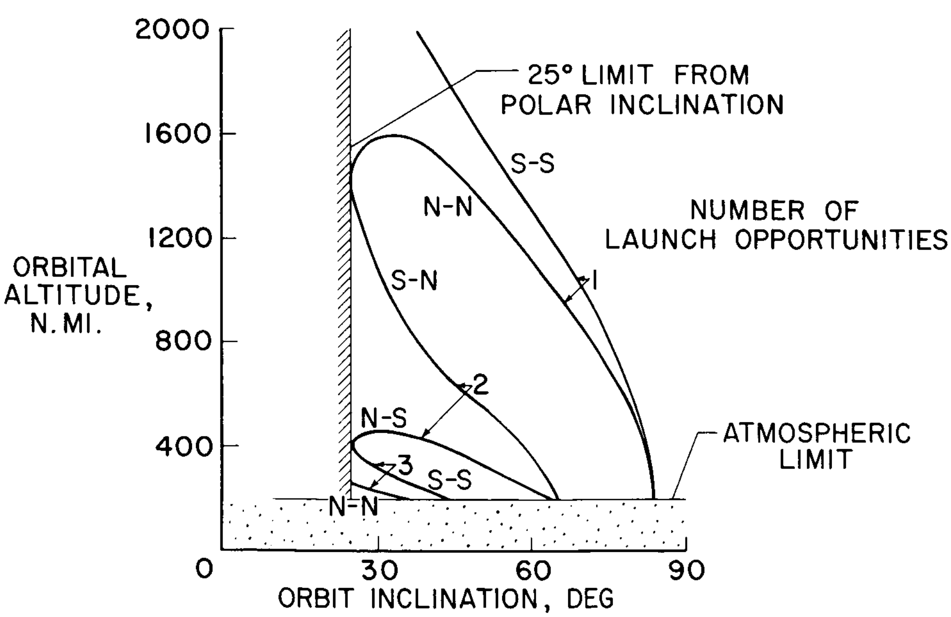

Figure 14.- Orbital altitude for tangential departure from circular orbits, 50-day stay.

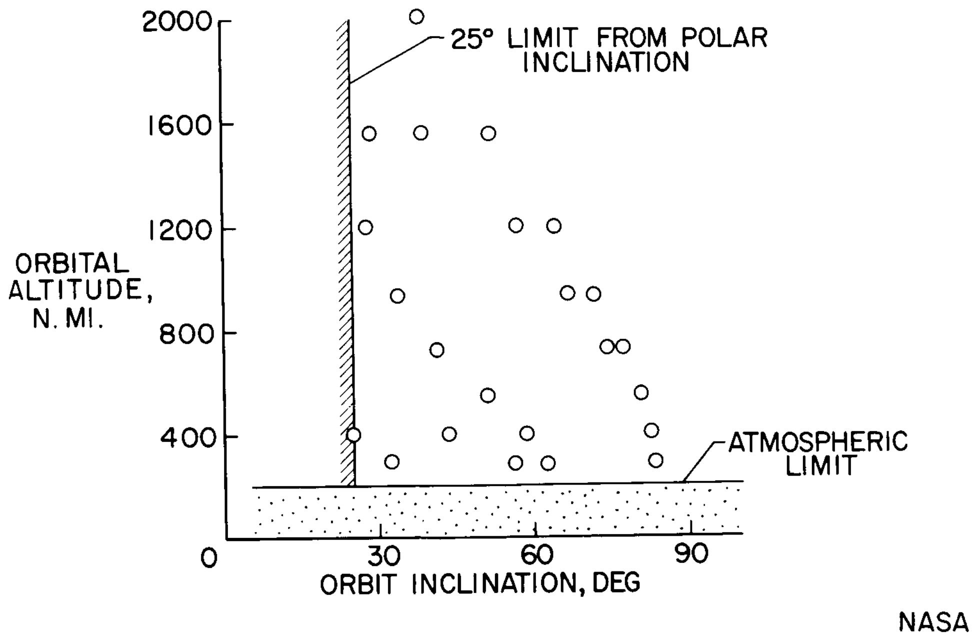

Figure 15.- Rendezvous compatible orbits for tangential departure from circular orbits, 50-day stay.

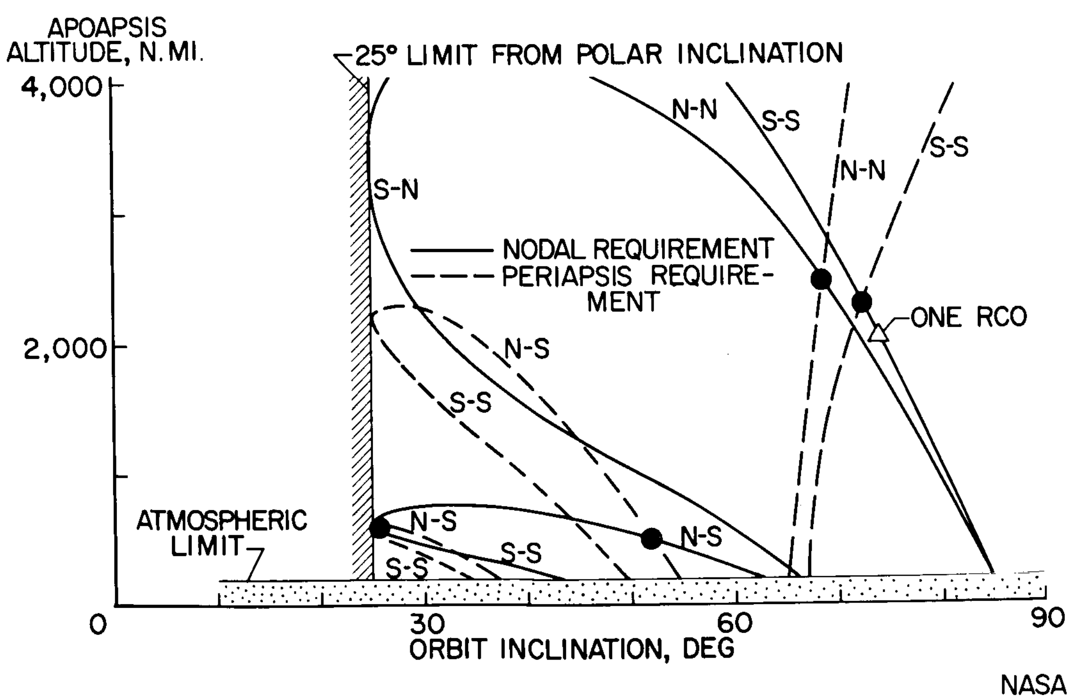

Figure 16.- Orbit requirements for tangential approach and departure at periapsis, 50-day stay.